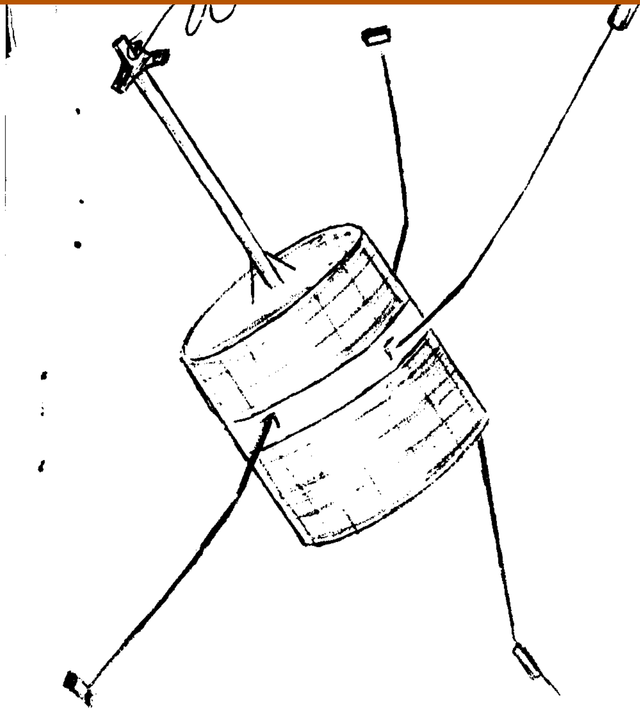

DEVELOPMENT OF THE INTERPLANETARY PIONEER SPACECRAFT

By

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INTRODUCTION

The development of a program for scientific exploration of space is a complex undertaking. Systems engineering brings together all the diverse elements within the program and correlates their activities so that the objectives of the program are met within the technical, fiscal, and schedule constraints. A number of tools, techniques, and procedures are available to the systems-engineering group to achieve this purpose. Those applied in the development of the Pioneer Program are described in this paper.

The Pioneer Project Office at the Ames Research Center, located approximately 40 miles south of San Francisco, was responsible for overall management and systems engineering of the Pioneer Program. TRW Systems in Los Angeles was the prime contractor on the Pioneer Program and was responsible for the management and systems engineering associated with the spacecraft and mission dependent ground equipment. The systems engineering aspects of the work performed at Ames Research Center and TRW Systems are discussed in the present paper.

The Pioneer mission objectives are summarized as follows:

(a) What: Systematic measurement of magnetic fields, plasma, high energy particles, and dust in interplanetary space.

(b) When: From minimum to maximum solar activity.

(c) Where: At large azimuthal distances from Earth between 0.8 and 1.2 AU (Astronomical Unit) from the Sun.

(d) How: Launch five Pioneer spacecraft.

It is anticipated that the systematic measurements will provide a better understanding of how solar disturbances are propagated through space, of the relationship of such disturbances to terrestial phenomena, and the relationship between solar and galactic fields. The time for making the measurements was selected because these interplanetary phenomena are affected strongly by the magnitude of the solar disturbances. The observations are made at large azimuthal distances from the Earth to investigate the spatial effects. To implement these objectives, five flights are to be launched at intervals of approximately 8 to 12 months, two of which will move ahead of the Earth with increasing time, and three of which will move behind the Earth with increasing time. The trajectories for the former lie between 0.8 and 1.0 AU from the Sun; those for the latter lie between 1.0 and 1.2 AU from the Sun.

To date, a Pioneer spacecraft has been launched in each of the above directions. The first was launched on December 16, 1965, and the second was launched on August 17, 1966. To the present, none of the spacecraft equipment or scientific instruments have experienced any malfunction which would prevent achieving the aforementioned scientific objectives. It is estimated that during the total of almost 1,000 days of operation, more than 5×10^9 bits of scientific data have been received by the ground stations and 12,000 commands have been transmitted to the spacecraft.

ORGANIZATION

The organization of the systems-engineering group has a major effect on its ability to fulfill its obligations and responsibilities. The organization of the Pioneer Project Office is shown in Figure 1. There are six units within the office with specific responsibility for the seven external subsystem elements and four units with responsibility for one function. Each unit is between 4 and 10 persons, depending on the complexity of the function of the group. The broad responsibilities of each subsystem unit are: (a) to be thoroughly familiar with the activities and performance of its associated element; (b) to be knowledgeable about future plans of the element; and (c) to keep other units fully informed about activities of its external element which may affect them. The second responsibility is very important. For example, at the start of design and development, the Delta launch vehicle was capable of boosting only 95 pounds to the velocity required by the Pioneer mission objectives. However, because of an awareness by the Launch-Vehicle-System Unit of planned improvements, it was possible to specify a total allowable weight of 130 pounds to the spacecraft and instrument elements at that time.

The organization of the Pioneer Program Office at TRW was very similar to that at Ames Research Center although it perhaps placed less emphasis on the Instrument, Launch Vehicle, and Data Handling Systems and more on the Spacecraft and Ground Operational Equipment than the Ames organization.

CONTRACT

The contract is valuable to the systems group in dealing with the principal external units. If properly written, the contract can motivate the external unit to achieve the desired technical performance. The contract with TRW Systems was a multiple-incentive type. Figure 2 shows the items for which the incentives were offered, namely, performance, schedule, and cost. The dollar value shown for each of the incentives is the maximum award or penalty corresponding to the indicated variation of the parameter. The variation within these limits was not linear. Except for the weight and schedule, the incentives are for four spacecraft. Weight and schedule incentives were for the first spacecraft only. Incentives for the fifth spacecraft have not yet been negotiated.

Incentive awards were offered for the four technical performance factors that were considered of prime importance to the achievement of the mission. TRW personnel were highly motivated by these incentives. To date, TRW has received the maximum performance incentive award on both Pioneer VI and VII.

Incentives are not a panacea and used indiscriminately can open a Pandora's box. It is essential that the systems group make certain that the incentives will produce results desirable to the program as a whole and not just to an individual contractor. Incentives for several Pioneer subcontracts for the scientific instruments were selected by the experimenter independently of the systems group. In those cases, incentives were applied only to performance and cost; an incentive for schedule was neglected. The subcontractor tends, therefore, to minimize cost and maximize performance with no thought of schedule. Yet a delay in delivery of a subsystem can cause a cost increase to the program larger than the savings from the contract or more than the performance improvement is worth.

DESIGN AND DEVELOPMENT PHASE - STUDY AND SPACECRAFT DESCRIPTION

The various aspects of systems engineering associated with the technical aspects of the program will be examined next. The first phase is design and development. During this phase, the entire program is shaped; sound decisions and direction can favorably affect all subsequent activities; whereas unsound decisions, misdirection, or, more likely, no direction, can adversely affect such activities.

The constraints for Pioneer were the performance of the launch vehicle and the size of the fairing which limit the size and weight of the spacecraft and, in turn, severely limit all spacecraft subsystems and scientific instruments.

The design requirements for Pioneer were that it provide:

1. A stable platform for the instruments
2. A 360° scan in the ecliptic plane
3. An induced magnetic field less than 1 γ (gamma) at the magnetometer
4. Operation in space for more than six months
5. A data system able to sample and transmit scientific and engineering measurements to Earth from large distances at bit rates as high as 512 bits per second
6. A command system to permit ground control of about 57 operational modes
7. A suitable thermal environment for the instrumentation

Before project approval, a design study - a power tool of systems engineering - was made by TRW Systems. It is important that such studies be made sufficiently early so that they are not subject to heavy pressures. Such pressures occur later in the program primarily because a large number of people await the solution of technical problems or because large costs are associated with changes. During the design study, only the merits of each option should be important.

The Pioneer spacecraft will be described to indicate some of the basic concepts obtained from the study. Although changes were necessary during the design and development phase, these basic concepts remained unchanged.

Figure 3 is a photograph of the spacecraft, and Figure 4 shows the spacecraft in the launch and flight configurations. The spacecraft is cylindrical and has three radial booms, an antenna mast on the cylinder axis at the forward end, and an antenna system for one scientific instrument at the aft end. The curved surface of the cylinder, except for a small band provided for viewing by the instruments, is covered with solar cells to supply the on-board power. Within the cylinder is a single platform on which all the electronic equipment for the spacecraft and six or seven schientific instruments are located. Thermal louvers aft of the equipment platform cover a portion of the platform area and open or close automatically to control the heat radiated from that surface.

The most important conclusion of the design study was that the spacecraft should be stabilized by spinning. (The nominal spin rate was 60 rpm.) The requirements for a stable platform and scanning were thus met without incurring any weight penalty. A spin axis perpendicular to the plane of the ecliptic further satisfies the scanning requirement for most of the mission. A cold nitrogen gas system is used to achieve this orientation within several days after launch. The three booms are required to augment the spacecraft moment of inertia about the spin axis to achieve the stabilization. One boom has a nozzle which, as part of the gas system, provides the torque for attitude control, and a second boom has a wobble damper at its end. The third boom contains the magnetometer sensor. The booms are folded against the antenna mast and the experiment antenna is folded against the cylinder during the powered flight so as to fit within the launch vehicle fairing. Immediately after the spacecraft separates from the launch vehicle, the booms and experiment antenna are deployed automatically.

A second important function of the booms is to allow the magnetometer at the end of one boom to be as far as possible from spacecraft equipment that induces magnetic fields. The problem of satisfying the design requirement for a low induced field strength at the magnetometer is, therefore, eased. Nevertheless, it was still necessary to select the materials and parts carefully for the entire spacecraft, and to use magnetic-compensation design techniques to satisfy this requirement fully.

The problem of communicating with the Earth from a spinning spacecraft at large distances was solved by using a high-gain antenna with a disk-like pattern in a plane perpendicular to the spin axis. Hence when the spacecraft spin axis is perpendicular to the ecliptic plane, the radiation from the antenna continuously illuminates the Earth. Since there is a significant reduction in the signal strength received at the ground with movement of the spin axis away from a perpendicular to the Earth-spacecraft line, the antenna gain pattern permits detection of spacecraft misorientation and is used in setting the desired orientation by ground command. Thus spacecraft attitude is measured by inherent properties of a communication system selected for communication at large distance.

To achieve the lifetime requirement, operation in space for more than six months, redundancy is used in a number of subsystems in the spacecraft. The orientation electronics is almost fully redundant with as much as four-fold redundancy in some portions because of its importance to the scanning requirement and its influence on the communication subsystem. The spacecraft also has redundant power converters, receivers, command decoders, and traveling wave tube power amplifiers. A portion of the digital telemetry unit is also redundant. Redundancy must be used judiciously since it increases the spacecraft weight. For Pioneer, this weight increase was approximately 13 pounds.

From the overall project viewpoint, the strength of the design study - conducted early by a small group working without the pressures to meet schedule, cost, or the urgencies of a complete program organization - also contributed to its weakness. In the Pioneer study there was no active participation by members of several important system elements since the program was not formally organized and some elements were not selected at that time. Thus between the completion of the design study and the start of detailed design, a number of changes were made in the systems. None of the fundamental concepts were changed, but refinements were made to take into account the new information pertaining to the interfacing subsystems.

SYSTEM ACTIVITIES DURING DESIGN AND DEVELOPMENT PHASE

Some of the more important activities of the systems group during the design and development phase were:

1. To prepare basic specifications
2. To conduct coordination meetings
3. To prepare interface specifications for major elements
4. To approve plans, procedures, and specifications
5. To attend design reviews
6. To review the impact of subsystem design or design changes on overall system
7. To support smaller elements within the program

In preparing the basic specifications, care was taken to assure that they covered all the basic requirements (design, fabrication, test, and handling) to meet the mission objectives, but that they did not prevent the designer from making intelligent trade-offs.

During the early phases of design, several coordination meetings were held. The Ames systems group chaired such meetings and the participants were, for example, the experimenters and spacecraft designer, or the ground station engineers and the ground station equipment designer. The need for coordination meetings in Pioneer-type spacecraft which carry a number of scientific instruments is great and perhaps distinguishes such a program from others in which the objectives are met by a single type of equipment supplied by few sources. Each experimenter uses a different instrument and his requirements frequently conflict with those of the other experimenters or spacecraft. The purpose of the coordination meetings was to review the technical requirements of the various experimenters, ~~and~~ the spacecraft, and the interfaces between them. Meetings were held whenever a significant decision was required.

Information presented at the coordination meetings was the basis for the interface specifications. Such specifications were thus constantly reviewed and revised as the design of the various subsystems proceeded. The interface specifications were very detailed. They were the primary means by which the systems group ensured the compatibility of the equipment supplied. Care was taken that all potential problem areas were covered. For example, a potential problem on spacecraft carrying a number of instruments is mutual interference, either conducted or radiated. The interface specification, therefore, stated the allowable frequencies that each assembly might generate so that it would not be in the range of susceptibility of another assembly. The information for such a specification was developed during one of the early coordination meetings for Pioneer, fortunately, since the initial survey indicated several possibilities of interference; the corrective actions were simple. In this case, the compromises necessary to avoid the problem had no adverse effect on the operation of the subsystems. However, usually the design choice for overall system improvement can hurt one or more of the subsystems. For example, on Pioneer there is a fuse in the power lead to each scientific instrument. The experimenters opposed this design arguing that fuses were notoriously unreliable and that a momentary overload that would have no lasting effect on the equipment could burn out the fuse and thus end the operation of the instrument. These arguments had merit from the viewpoint of the individual experimenters; from the systems viewpoint, the fuse was deemed necessary to prevent a permanent overload in the event of a short circuit in any instrument.

Discussions in the coordination meetings also brought to light potential problems which could necessitate changes to the basic requirements; the systems group had to evaluate each and decide on the proper action. For example, the Deep Space Network/Spacecraft meetings indicated the advisability of providing full communication power for initial acquisition and providing a means for sampling and recording data during nontracking periods. The basic specification was modified to incorporate these changes in the spacecraft.

The systems group also evaluated plans, procedures, specifications, and parts that each element was using to make certain that overall requirements were met.

The Pioneer systems groups spent considerable time reviewing designs. As many as three design reviews were held for each spacecraft subsystem, each instrument, and each ground-equipment subsystem. Documentation was usually made available for study several weeks in advance of a review. Personnel from the systems groups at both the Project Office and TRW attended the design reviews for each of the spacecraft and ground-equipment subsystems. Design engineers from all subsystems having an interface with the subsystem being reviewed participated. The meetings were formal, detailed minutes were taken, and, most important, subjects requiring further action were assigned, with a definite completion date, to individuals. Design reviews for the scientific instruments were attended only by the systems group from the Project Office.

The importance of the design review cannot be overstressed, for here the design engineers from the interfacing subsystems exchanged background information and discussed the various trade-offs leading to the selected design. It is the best means of preventing future problems. In addition, the information presented was invaluable to the systems group when it reviewed the design of each program element since it was better prepared to evaluate options presented during the review. The information obtained in the reviews was also of great use in planning the flight operations.

A continuing activity of the systems group was assessing the impact of a subsystem design or design change on the overall system and vice versa. An example is the mutual effects between the orientation subsystem and the powered-flight trajectory. Immediately following separation of the spacecraft from the launch vehicle, the spacecraft automatically orients itself so that the spin axis, and hence solar cell array, are perpendicular to the spacecraft-Sun line. The maneuver is controlled by two Sun sensors; the sensors are opposite to one another on the spacecraft "equator" with one scanning almost the entire upper hemisphere and the second the lower hemisphere. The sensors must be designed so as to have a blind area within 10° of the spin axis at both ends to prevent an undamped or divergent oscillation of the spin axis if the spacecraft is wobbling at separation and the spin axis is pointing near to the Sun. On the other hand, the powered-flight trajectory must now be shaped to preclude the possibility that the spin axis might point to within 10° of the Sun following separation and neither sensor would see the Sun so as to initiate the maneuver. A considerable effort was expended by the systems group, first in determining the seriousness of the potential problems, and then assuring itself that a solution was possible. The systems group must be continuously on the alert to detect these potential problem areas. Problems such as this example can be easily overlooked, or their assessment neglected, because of their apparent triviality; yet they can have a significant effect on the mission.

In the Pioneer Program, some of the scientific instruments are supplied by research organizations who may not be able, because of lack of equipment or experience, to perform many of the activities necessary for meeting the mission objectives. The responsibility for performing such activities was assumed by the Project systems group which provided considerable support during the design of the scientific instruments as well as during the fabrication and test phases. For example, magnetic specialists provided approved parts lists for use by the experimenters and were available for consultation. A magnetics laboratory was set up in which parts for the instruments were magnetically screened and the magnetic characteristics of each instrument were measured. Types of electronic parts that were few in each instrument but common to most instruments were purchased in a lot to expedite delivery and reduce cost. With respect to reliability and quality control, essentially the same requirements were imposed on the experimenters as on the spacecraft contractor. Generally these requirements are formulated with the complex organization of the spacecraft contractor in mind. Reliability and Quality Control personnel from the Project Office were available for interpreting these requirements to suit the individual experimenter. They were available for consultation during the design phase and later monitored the fabrication and test phases.

FABRICATION

While Pioneer was being fabricated, an important activity of the systems group was again the assessment of the effect of required subsystem design changes uncovered during fabrication on the remaining subsystems. At TRW, each engineering change to spacecraft subsystems was reviewed by a formal Change Control Board. Personnel from the systems group at TRW were members of this board so that the group would be aware of proposed changes, could examine their effect on the overall system, and could disapprove them if thought necessary. Another area of activity for the systems group was concerned with monitoring and assuring proper quality control.

TEST PROGRAM

The purpose of the test program is to determine system performance and to identify problems. The program, therefore, must be comprehensive and must be performed carefully and thoroughly. The various tests in the program can be grouped into four types. In the first type, environmental tests, the equipment was subjected to vibration, acceleration, shock, high and low temperatures, and vacuum. The second type, functional tests, were essentially "go - no go" tests to verify that the equipment was operating and were performed after each environmental test. In the third type, performance tests, detailed measurements were made on a number of subsystems to determine if their performance had deteriorated during the overall test program. Measurements were also made of the induced magnetic fields of each subsystem individually and then of the complete system. In the fourth type, compatibility tests, each scientific instrument was tested with a spacecraft simulator before integration on the spacecraft to verify that it would be compatible with the spacecraft. (This simulator was also valuable for trouble-shooting instrument malfunctions.) In other compatibility tests, detailed measurements were made of each subsystem while it operated with all other subsystems on the spacecraft and of the complete system operating in conjunction with a Deep Space Station.

The environmental, functional, and performance tests were performed on the individual assemblies and on the integrated system. The assembly tests were completed in three to five weeks, excluding any time for repair, and the system tests were completed in about five and a half months.

The environmental tests were conducted at two levels - a qualification level and an acceptance level. The mechanical loads applied during the qualification tests were 50 percent greater than those expected in flight and applied during the acceptance tests. In addition, a wider range of temperatures and input-power voltages were covered in the qualification tests than in the acceptance tests.

SYSTEM ACTIVITIES DURING TEST PHASE

The principal activities of the systems group during the test phase were as follows:

1. Monitoring tests
2. Participating in post-test critiques and Test Review Board
3. Reviewing failure reports
4. Participating in the Failure Review Board

Previously, the group had prepared test requirements and had approved plans and procedures for use during the test to make certain that they conformed to the requirements.

Monitoring the tests and participating in critiques served several needs. The results of systems tests may indicate: (a) that one or more of the subsystems must be modified because of a lack of compatibility, (b) that the system is incompatible with another system not a part of the test, or (c) that the specified tests do not adequately establish the performance of the system. Correcting deficiencies of this type is within the purview of the systems group; detail knowledge of the test results is necessary to make the correct decision.

Within several weeks after a post-test critique, the Test Review Board evaluated the results from any analyses or investigations which had been undertaken because of anomalies during the tests. The systems groups participated to make certain that there were no items left unresolved, that the equipment passed the tests successfully, and that if necessary, other elements within the program would be informed of the results of the tests.

The failure of any assembly of the spacecraft and instrument systems in qualification tests or acceptance tests was reported formally to the Project Office within 48 hours with a description of the failure and the corrective action taken. Such reports are invaluable in recording the progress of the tests and in detecting recurring problems or trends in failures. They permit early access to information which eventually may result in significant effects on other subsystems. They also provide a history of each assembly which is useful in the evaluation of the reliability and quality of the flight equipment. One is always wary about flying equipment that has failed and has been repaired a number of times.

Participation in the Failure Review Board was an extremely important function of the systems groups. Here the failure, its cause, and the corrective action taken were thoroughly evaluated. The Failure Review Board required the cognizant engineer to be thorough in evaluating failures; it had the right to reject an evaluation and request further study. A case in point concerns the fuses in the instrument power systems mentioned previously. It illustrates the need for rejecting the obvious at times and performing a detailed evaluation. Several failures during the test program seemed to substantiate the fears of the experimenters that fuses were unreliable. A plausible explanation could have been that the fuse was merely performing its function by preventing a momentary power overload and hence damage to the remainder of the equipment. Nevertheless, to satisfy the requirement of the Failure Review Board, a comprehensive examination of the problem was undertaken. A test program was undertaken which eventually showed that the failures were caused by the techniques used in assemblying the fuses to the fuse block. The block was then redesigned and new flight connectors of the modified design were fabricated and installed on the spacecraft. No further failures occurred.

GENERAL COMMENTS

The activities of the systems groups of Pioneer covered a wide spectrum; yet all these activities followed a few general guidelines. Within its area of responsibility, the group must continually give attention to the most minute detail; the spectacular is rare. Nothing should be left to chance or assumed. Many problems result from misunderstandings during oral discussions; hence, direction and information should be in writing. Meetings should have a well defined purpose, be formal, and be well documented. All items requiring action should be assigned to one person with, where possible, a date for completion.

FLIGHT EXPERIENCE

To conclude the paper, the flight experience for Pioneer VI and VII will be reviewed briefly. To date, this experience has been limited because there have been no failures to prevent achieving the mission objectives. Malfunctions have occurred, however, on both spacecraft. On Pioneer VI, a slow leak developed in the orientation system. At the end of six months, the gas supply was exhausted. The spacecraft attitude was as required before that time and the need for any further adjustments is not anticipated at this time. It was concluded from an investigation by TRW that the seat of the regulator valve must have been damaged by vibration during powered flight. Changes were made to the structure supporting the valve to reduce the vibration loads on Pioneer VII. Results indicate the fault was cured.

On Pioneer VII, the performance of one of the traveling wave tubes deteriorated. For certain operating conditions, the current and temperature became high and the output power reduced. It is believed that the tube was operating too close to its point of instability. On future Pioneers, the tubes will be adjusted so as to operate farther from this point. Fortunately, the Pioneer spacecraft have redundant traveling wave tubes.

An anomaly has also occurred with the orientation subsystem which fortunately occurred after the spacecraft had been correctly oriented. Approximately seven months after launch, attempts to precess the spin axis by ground command were apparently unsuccessful; telemetry information indicated no operation of the nozzle valve. Three and one-half months thereafter, a second attempt was made to precess the spin axis. In this case, 2/3 of the system operated correctly. Both attempts were made so as to determine any small change in attitude due to solar pressure. The cause of the anomaly is still under investigation. We have speculated that a possible cause is a deterioration of the sensitivity of the Sun sensors which control the maneuver due to bombardment of high energy protons during solar flares earlier this year. During the second attempt, which was partially successful, the intensity of solar illumination at the sensors was about 20 percent greater than during the first attempt because the spacecraft was closer to the Sun. If this hypothesis is correct, it will be necessary to reduce the threshold of the sensors on future Pioneers to prevent a repetition.

The redundant receivers and command decoders on each spacecraft have been used alternately. This equipment operates continuously; the receiver is selected by the frequency of the ground transmitted signal and the decoder by the command message. Other redundant equipment, such as that in the digital telemetry unit on both spacecraft and the traveling wave tube on Pioneer VI, has not been used. This equipment must be switched by sending commands to the spacecraft. So long as the equipment initially used continues to operate flawlessly, we do not take any action which might induce a malfunction.

PIONEER PROJECT OFFICE ORGANIZATION

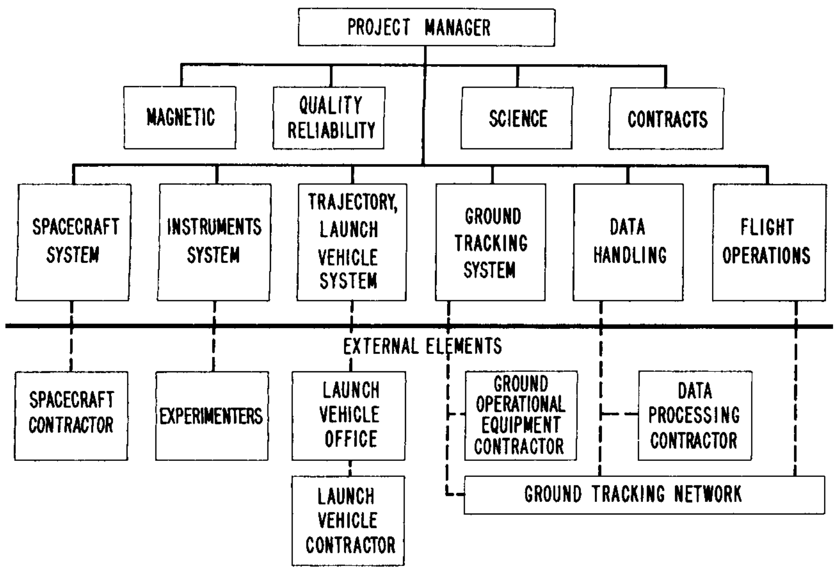

Figure 1

PIONEER SPACECRAFT INCENTIVES

PERFORMANCE

WEIGHT:	+ \$150,000 TO − \$300,000 FOR −5 TO +5 LB FROM TARGET
MAGNETIC:	+ \$195,000 TO 0 FOR 0 TO 1γ
ORIENTATION:	\$30,000 PER SUCCESSFUL ORIENTATION PER SPACECRAFT
LIFETIME:	+\$720,000 TO −\$360,000 FOR 180 TO 0 DAYS IN ORBIT

SCHEDULE

0 TO − \$120,000 FOR 0 TO 60 DAYS LATE

COST

CEILING COST:	125% OF TARGET
SHARING:	+20% OF COST SAVING BELOW 95% OF TARGET
	−10% OF COST ABOVE 105% OF TARGET

Figure 2

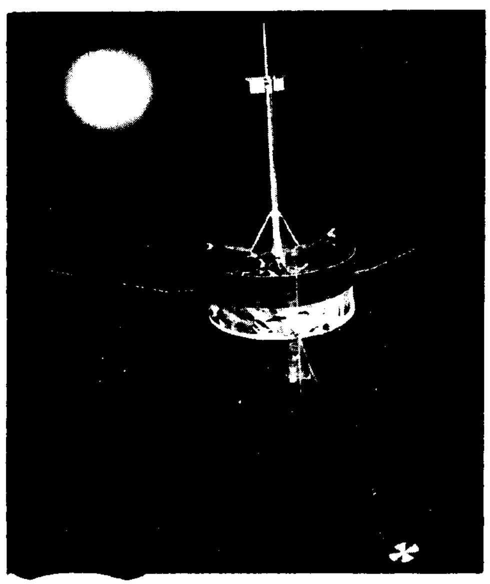

Figure 3

PIONEER SPACECRAFT

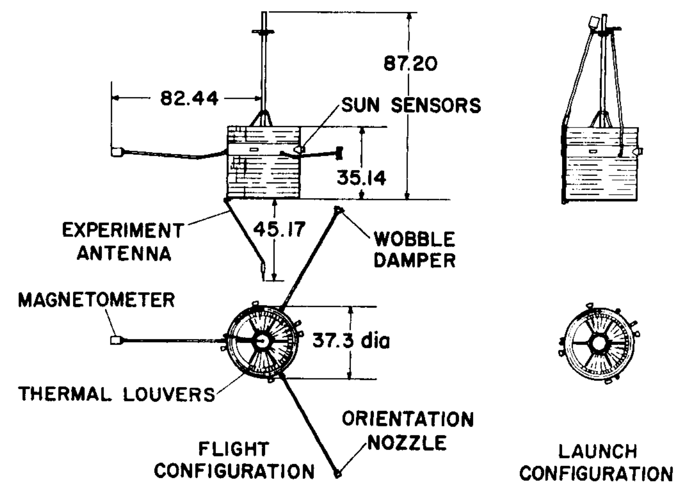

Figure 4

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA